PILOT CRYO TUNNEL: ATTACHMENTS, SEALS, AND INSULATION

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ABSTRACT

This paper describes tests performed in evaluation of flange attachments, seals, and the structural support insulation for an operational pilot cryogenic wind tunnel. The overall dimensions of the pilot tunnel are 32-1/_ feet (9.9 meters) long, 12 feet (3.7 meters) high, and 4-foot (1.2 meters) maximum diameter, with a 13.5-inch (0.34 meter) octagonal test section, and a 12/1 contraction ratio. The closed loop tunnel at NASA Langley Research Center was designed for operation at near-cryogenic nitrogen temperature and required knowledge of material behavior and performance in addition to that available from the literature. The design conditions for the tunnel are pressures up to 5 atmospheres (507 kPa) and temperatures from -320° F (78° K) to +120° F (322° K). The cold temperature, in conjunction with the pressure, required tests and studies of the following areas: Compatible bolting, adequate sealing, and effective insulating materials. Flange attachments (continuous threaded "studs" or "headless bolts"), seals, and structural support insulations were evaluated by utilizing several different tests which simulated the actual tunnel configuration. The evaluation of flange attachments considered bolting based on compatible flanges, attachment materials, and prescribed bolt elongations. Various types of seals and seal configurations were tested

to determine suitable sealing and reusability under the imposed pressure and temperature loadings. Finally, the temperature profile was established for several materials used for structural supports. The data from these investigations and/or evaluations were utilized in designing an existing cryogenic tunnel.

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INTRODUCTION

The detail design of a Pilot Cryo Tunnel at Langley Research Center (LRC) required the knowledge of material behavior and performance in addition to that from the literature. The Pilot Cryo Tunnel was designed to operate at pressures up to 5 atmospheres (507 kPa) and temperatures from -320° F (78° K) to 120° F (322° K). An elevation of the closed loop circuit of the Pilot Cryo Tunnel is shown in Figure 1. The over/under arrangement of the test section and return leg was selected. Other features of the tunnel are the shell insulation (Fig. 2) and the anchor point of the tunnel (Fig. 3). The tunnel shell insulation consists of fiberglass cloth adjacent to the tunnel shell followed by alternate layers of urethane foam and glass cloth with an outer vapor barrier coating of fiberglass and polyester resin (FRP). Each tunnel section was insulated in the shop to a point short of the flange. The final flange insulation, inorganic mineral wool, and precut pieces of urethane foam covered with an "FRP" vapor barrier was installed at the site. The

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anchor was optimized to maintain tunnel centerline location while allowing shell movements from thermal effects. Where necessary information or experience was lacking, design and structural concepts were verified with tests of the following prior to construction:

(1) A bolted flange model to determine the necessary bolt load which would maintain a seal near cryogenic nitrogen temperature and yet not overstress the bolt at ambient conditions.

(2) A gasket and "o"-ring model to insure seal integrity at design pressures throughout the operating temperature range.

(3) A model of the support structure to verify that the design temperature range would not preclude use of economical A-36 carbon steel for the massive base portion of the support structure and to verify insulation characteristics and its structural integrity at design temperatures.

This paper also presents the results of no-load and load bolting conditions for compatible flange and bolt materials. Tests were run to determine a suitable material to insure sealing and seal reuse under the imposed pressure and temperature restraints. Finally, an investigation was performed to establish the temperature variation across two structural support insulation candidates between the tunnel structure and supports.

DESCRIPTION

A Pilot Cryo Tunnel, a small scale high Reynolds number Transonic Wind Tunnel having the unique capability to operate near cryogenic nitrogen temperature, has recently been designed, built, and operated by Langley Research Center. The cryogenic tunnel concept promises substantial

advantages in aerodynamic testing; but, because of the wide temperature variation, numerous engineering, construction, and operation problems need to be overcome. To prove the concept and gain experience, LRC undertook the design and construction of the world's first known "cryogenic" tunnel utilizing nitrogen as the working medium. Figure 4 is an isometric drawing of the tunnel with accompanying photographs of various tunnel parts in their completed state prior to tunnel assembly. The tunnel is approximately 30 feet (9.1 meters) in length with a maximum diameter of 4 feet (1.2 meters). It has a 3,000-hp (2.238×10^6 watts) single-stage fan drive, multiple smoothing screens, a 12 to 1 contraction ratio, and a 13.5-inch (0.34 meter) octagonal-slotted-transonic test section. The tunnel has a single structural anchor point at the fan location. All other support points feature a sliding pad design to accommodate thermal contraction and expansion. The design requirements for the tunnel were as follows:

Stagnation pressure:	1.1 atm (112 kPa) to 5.0 atm (507 kPa)
Stagnation temperature:	+120° F (322° K) to -320° F (78° K)
Mach number:	0.2 to 1.4
Reynolds number:	(at $M = 1$) 9×10^6

The design began in December 1972 and the tunnel has been operational since September 1973.

DESIGN APPROACH

The tunnel pressure shell was fabricated from 6061-T6 aluminum material because of its (1) excellent proven properties at cryogenic (-320° F) (78° K) temperature, (2) availability, and (3) ease of fabrication. Studs of

2024-T4 aluminum were used for bolting because of their compatible coefficient of linear expansion with the 6061-T6 aluminum flanges and the high yield strength at cryogenic temperatures. Nuts of 304 stainless steel to minimize galling and galvanic corrosion were secured on each end of a threaded rod (stud). The stud extends through the flange, permitting uniform thermal expansion or contraction, and minimizes stress concentrations.

The tunnel shell was fabricated and installed in flange-connected sections (Fig. 4) since frequent removal of particular sections of the tunnel was required. It was desirable, therefore, to select a reusable seal which would be compatible with the gaseous nitrogen test medium and provide a leak free tunnel under the pressure and temperature ranges. Numerous materials and configurations appeared to meet these requirements: Hollow stainless steel "o"-ring, solid aluminum "o"-ring, hollow stainless steel teflon-coated and vented "o"-ring, stainless steel teflon-coated "V" seal, virgin teflon resin and pulverized glass fiber (fluorogreen) flat gasket, the same type fluorogreen gasket-split and rebonded, and a Viton-A rubber "o"-ring.

The tunnel structural support insulation at cryogenic temperatures must not only permit expansion and contraction of the tunnel, but also withstand vibration and compressive loadings. A thermal analysis of the insulation and the structural stands provided the basis for selection of tunnel support materials. The materials and configurations for the studs, seals, and support structure were designed to the ASME Pressure Vessel Code (Ref. 1) and tested to confirm their performance.

TEST PROCEDURES

Bolting tests. The test configuration to calibrate the studs for a typical flange of the tunnel is shown in Figure 5. Studs are indicated as 1, 2, and 3. The nuts on each end of studs 1 and 3 were tightened to a strain analogous to a stress slightly less than yield. The threads of stud 2 were removed for a length equivalent to the flange thickness for installation of strain gages. Nuts on each end of stud 2 were installed loosely, with the resulting stud and flange unit instrumented with thermocouples (TC), see Figure 6. The entire unit was lowered into a tank of liquid nitrogen (LN_2) until the lower surface, indicated as "A," contacted the LN_2. The thermocouple readings and stud strains are tabulated in Table 1. The strains are a function of time and maximum temperature differential between thermocouples. After this test, the unit was covered with polyurethane PE-2 insulation (Fig. 7). Stud 2 was tightened to an elongation equal to studs 1 and 3 and retested. The thermocouple readings and stud strain due to thermal cooling for a period of 3 hours are tabulated in Table 2.

Seal tests. A test unit consisting of a seal between bolted flanges was constructed (Fig. 8) to study sealing properties. The stud loads were prescribed to obtain either metal-to-metal contact for "o"-ring seals or stud elongation for the gasket seals. The stresses in the studs, to be within ASME Code allowables, cannot be greater than 10,000 psi (69 MPa); therefore, the test parameters (the number of studs, stud loads, and sealing area) were equated to the flange and seal design conditions. The unit at room temperature was subjected to the design pressure of 60 psig (515 kPa) using helium gas. If no leaks were found after 20 to 45 minutes,

it was depressurized, submerged in a test tank (Fig. 9), and cooled to LN_2 temperatures. The unit was again subjected to the design pressure and the leak rate recorded. It was then depressurized, removed from the test tank, later repressurized at room temperature to check for leaks, and finally disassembled to inspect the seal. The seal was reassembled in the flange test unit and the complete test procedure repeated. The test results are listed in Table 3, and configurations of the various seals are shown in Figure 10.

<u>Structural support insulation</u>. A test apparatus, to confirm the thermal resistance of the support insulations and the temperature profiles of the support stand, was fabricated as shown in Figure 11. The apparatus for the first test insulation, two 1/2-inch (12.7 mm) thick teflon sheets, consisted of a stainless steel fin and an aluminum tank simulating the support and tunnel attachment structures, respectively. The fin was attached with four 1-inch (25.4 mm) studs to an aluminum plate on the tank. Seven thermocouples were located on the test apparatus: One above the fin and sandwiched between the teflon sheet and the aluminum tank, one between the teflon sheet and stainless steel, and five along the length of the fin. The tank (Fig. 11) was filled with LN_2 and the temperatures monitored. The test results for two runs (the second allowing time for temperature stabilization) are shown in Figures 12 and 13, respectively. The same general apparatus (Fig. 11) was used for the glass-phenolic honeycomb. The 3/8-inch (9.5 mm) honeycomb cells (2.2 pounds/ft^3 (35.2 Kg/m^3) density) were bonded to the aluminum plate and the stainless steel fin with two layers of fiberglass laminate. The test insulation was encapsulated with a glass tape sealant

which was covered with a 50-50 mixture of epoxy-versimite resin. Thermocouples were installed the same as for the teflon test with the results shown in Figure 14. The temperature drop stabilized after 2 hours for both the teflon and the honeycomb insulation. In either case the fin temperature profile for the support structure was no cooler than -20° F (244° K) when located 6 inches (152 mm) or farther from the warm face of the insulation.

RESULTS AND DISCUSSION

Since the shrinkage of the "stud-flange" model due to cooling was negligible under a no-load condition (Table 1), the calibration of the elongation need not be applied. The temperature differential (Table 2) between the flange and stud was low enough to assure that the flange would not shrink faster than the stud; therefore, the preload was not reduced below a value sufficient to withstand internal pressure. The stud strain when converted to stress confirmed that the flanges would not leak at the tunnel design pressure. It was thus permissible for the flange and stud configurations to be designed normally in accordance with the ASME Pressure Vessel Code (Ref. 1). This design procedure was automated for use on an electronic, programable calculator. All the seals except three (Table 3) performed satisfactorily at room and cryogenic temperatures. The solid aluminum and hollow stainless steel "o"-rings did not seal at room temperature. Fluorogreen E-609 flat gaskets proved best and teflon-coated 321 stainless steel "o"-rings were the next best in performance considering sealing, economy, and reusability. Since fluorogreen was not available in sizes larger than 36 inches (0.914 m) outside diameter, stainless steel was used for the larger sizes. The Viton-A seal material was ruled out since it becomes

brittle at temperatures below -100° F (200° K) and cannot withstand vibrational loadings. The teflon "V" seal was reusable; however, the required tolerances and finishes on adjoining surfaces could be difficult or costly to obtain. During the initial tunnel checkout, it was necessary to open a fluorogreen flange joint on the tunnel shell. On reusing the gasket, the joint could not be sealed even by exceeding the initial design bolt load. However, after allowing the joint to remain loaded overnight, it could be sealed at bolt loads equal to or below design levels. Thus, it was established that all fluorogreen gaskets would be loaded to prescribed values, allowed to set for 12 to 24 hours for initial gasket cold flow, and then reloaded to prescribed values.

Either the teflon or honeycomb would be sufficient as a structural insulator. Although the glass-phenolic honeycomb tested slightly superior, teflon was chosen for its ease of fabrication, low coefficient of friction, and strength under compressive and vibrational loads. Maintaining the fin temperature profile within the ASME Code temperature limits dictated the use of 300-series stainless steel for the first 7 inches (178 mm) of the support structure and allowed A-36 carbon steel for the remainder.

CONCLUSIONS

The three tests discussed in this paper verified material behavior and performance where information or experience was lacking. The flanges and studs, when preloaded to withstand internal pressure, can be designed normally in accordance with codes. The flat fluorogreen gaskets and teflon-coated 321 stainless steel "o"-rings provide a tight and reusable

seal for near-cryogenic nitrogen temperature and 5 atmospheres (507 kPa) pressure requirements. Teflon structural support insulation with a 300-series stainless steel spacer protects the remaining structural steel from temperatures below -20° F (244° K); thus, economical A-36 carbon steel can be used for structural supports of a cryogenic tunnel. Although proven for one specific application, the results from the bolting, sealing, and structural support insulation tests should be applicable for general use in cryogenic work.

APPENDIX.- REFERENCES

1. The American Society of Mechanical Engineers: ASME Boiler and Pressure Vessel Code, Pressure Vessels, Section VIII, Division 1, 1971.

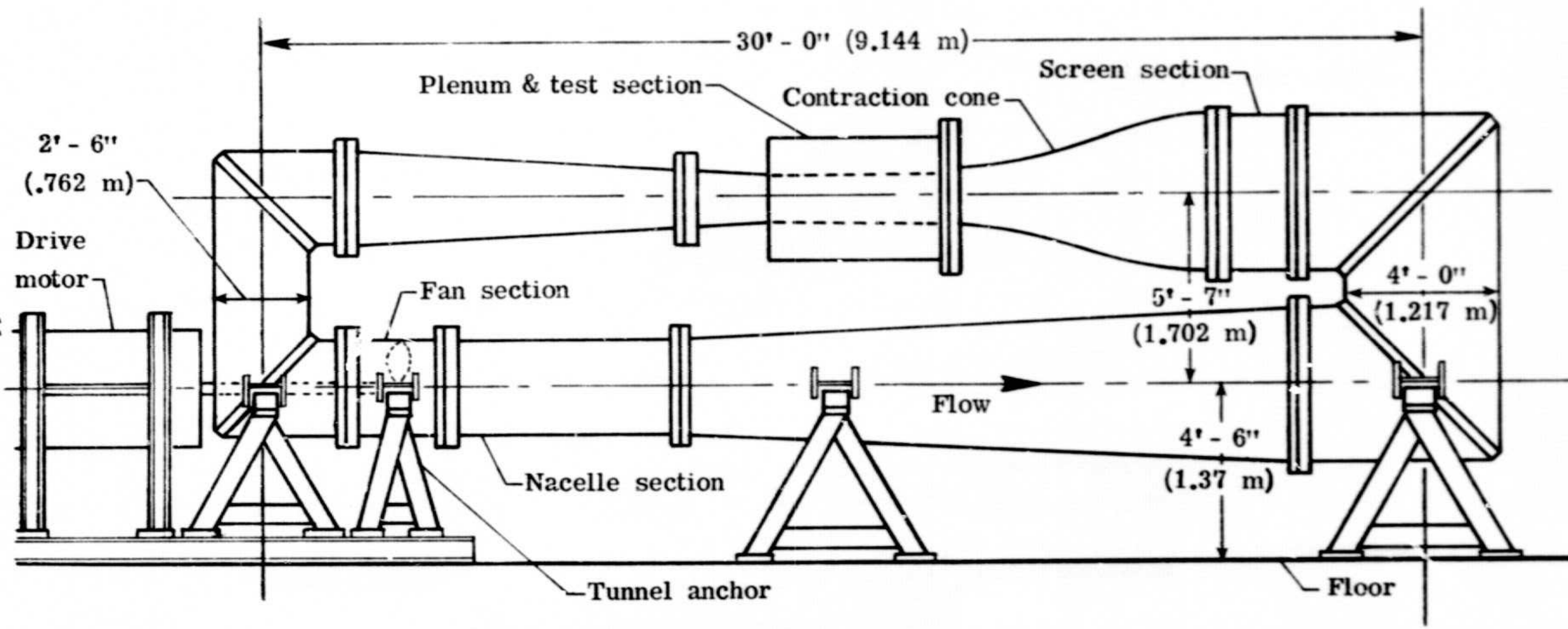

Figure 1. Pilot Cryo Tunnel - elevation.

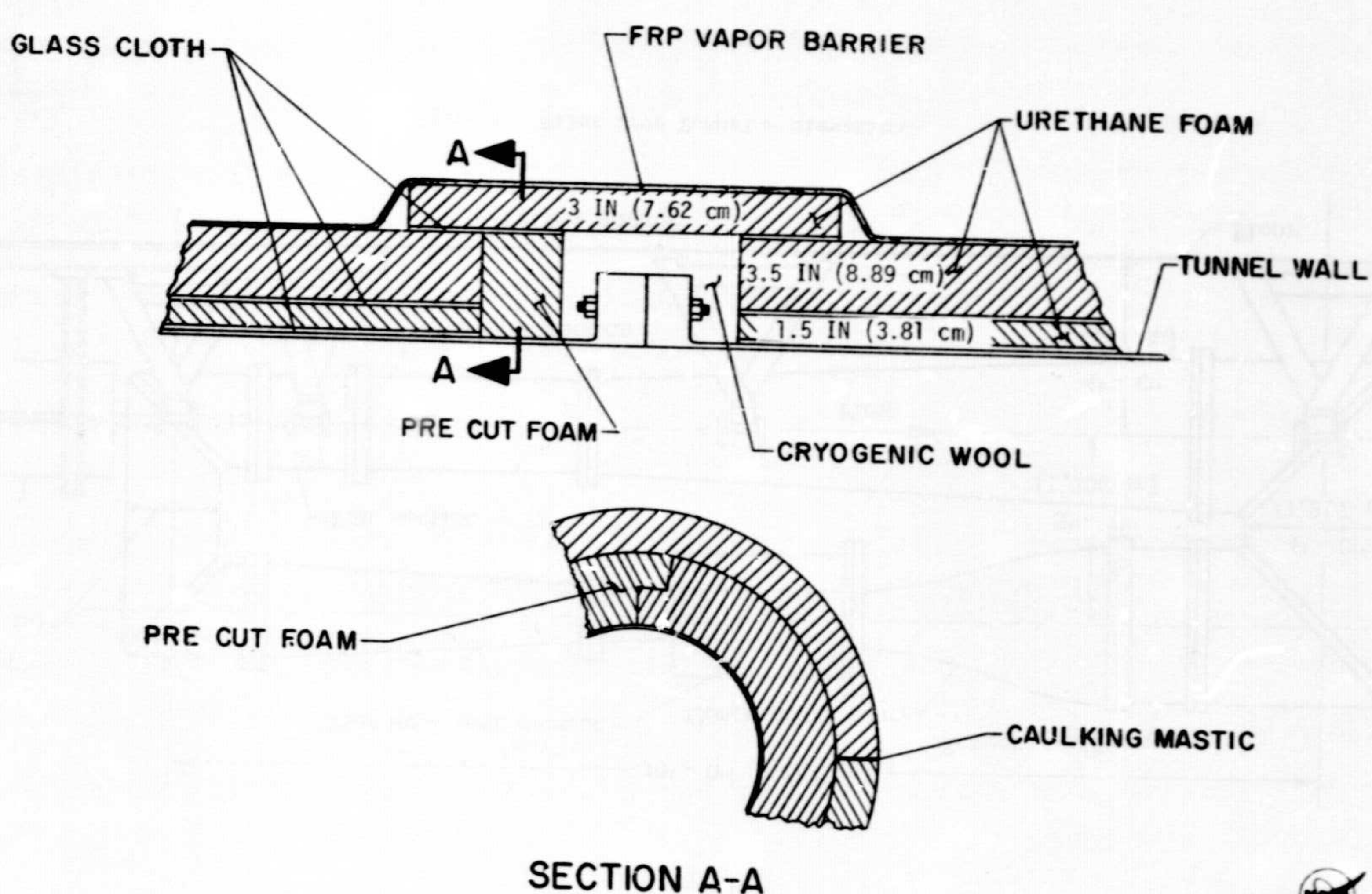

Figure 2. Pilot Cryo Tunnel insulation details.

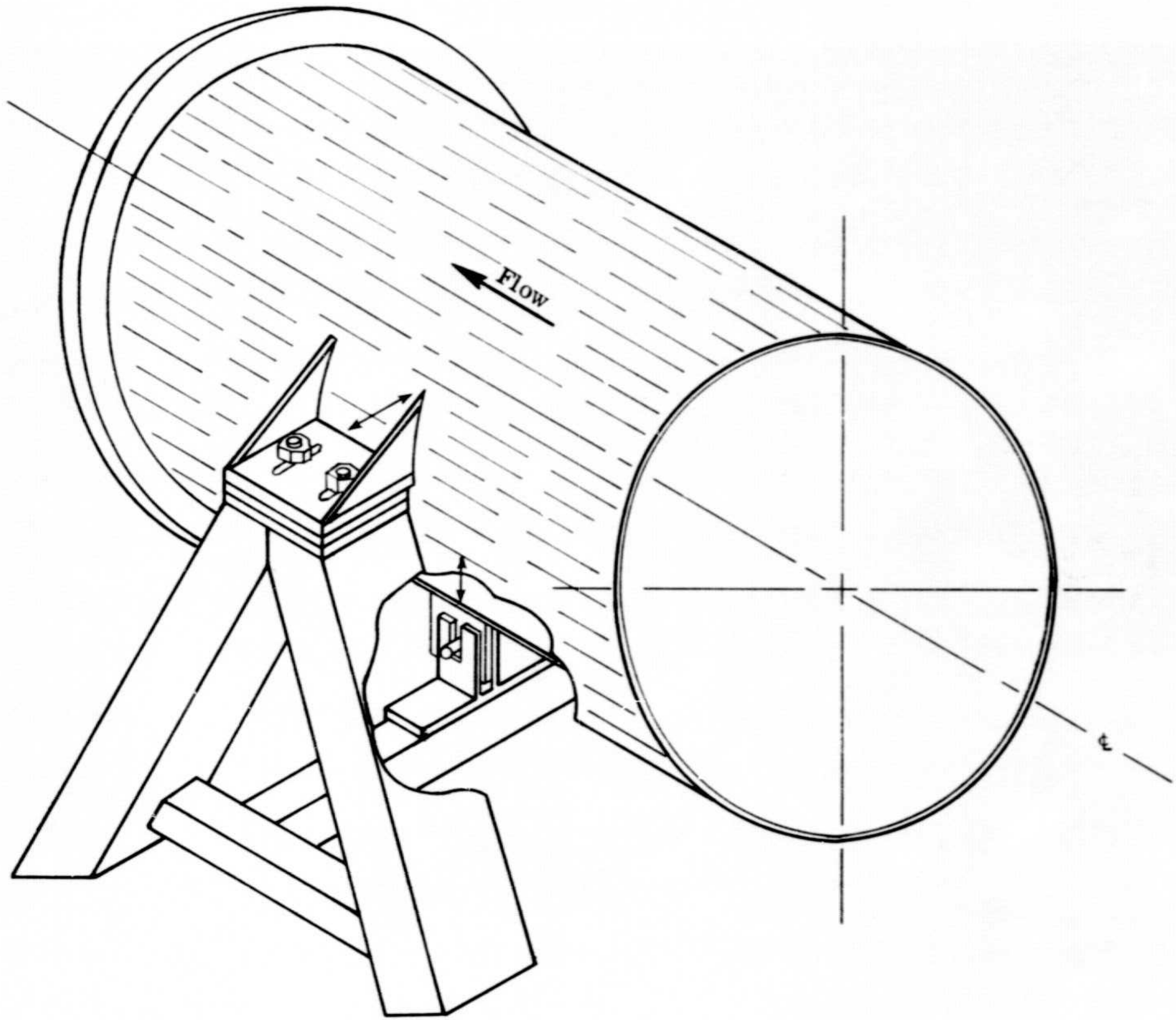

Figure 3. Pilot Cryo Tunnel anchor point.

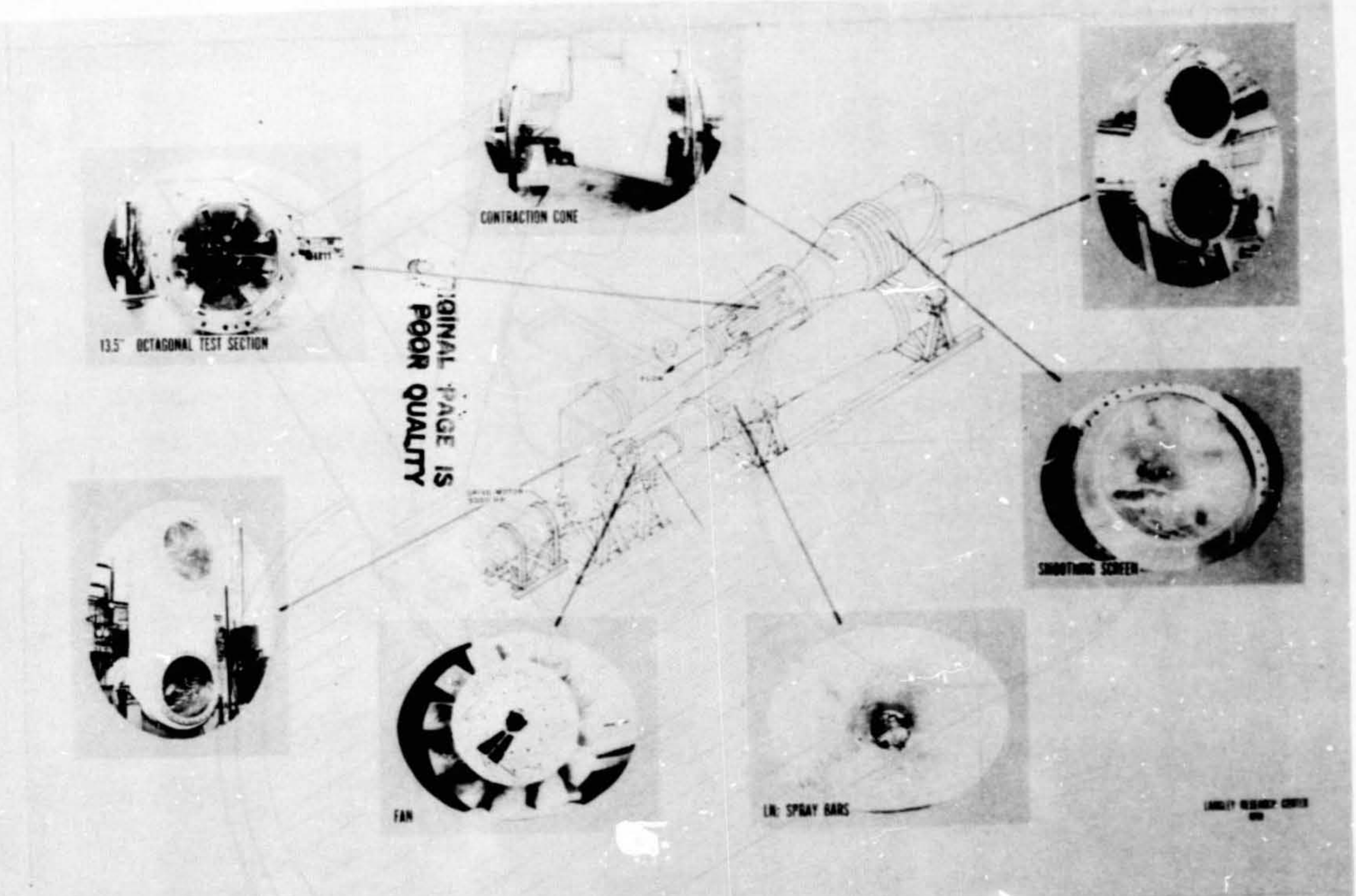

Figure 4. Pilot Cryo Tunnel isometric.

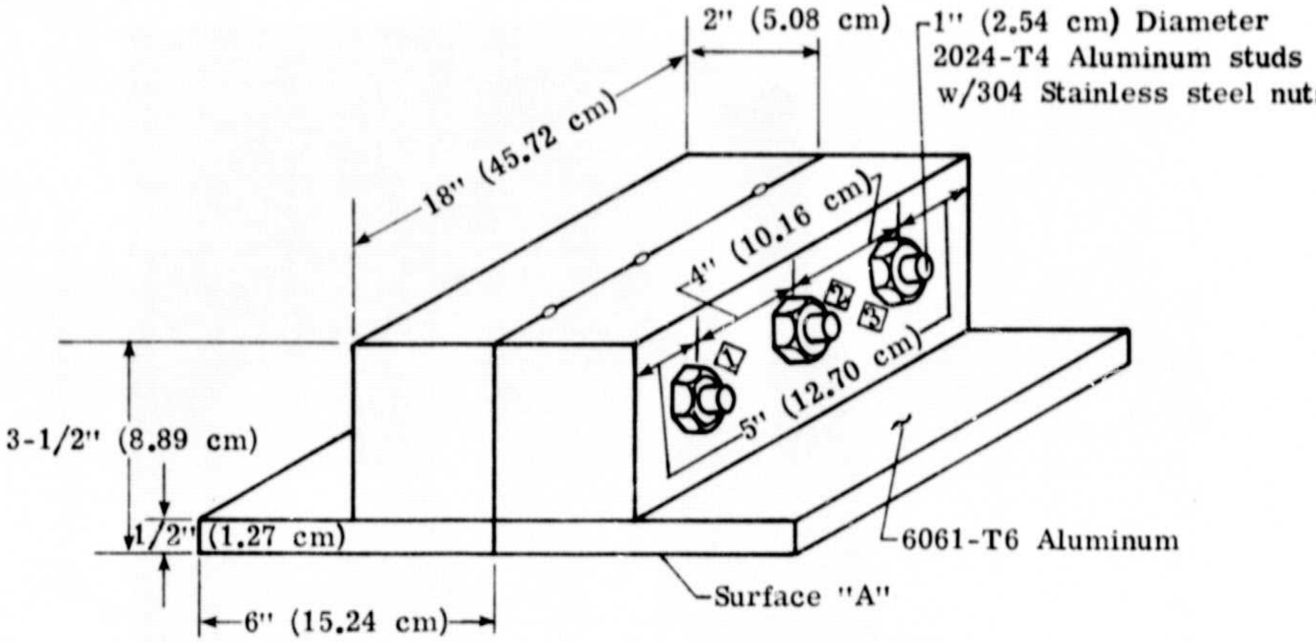

Figure 5. Pilot Cryo Tunnel bolt calibration configuration.

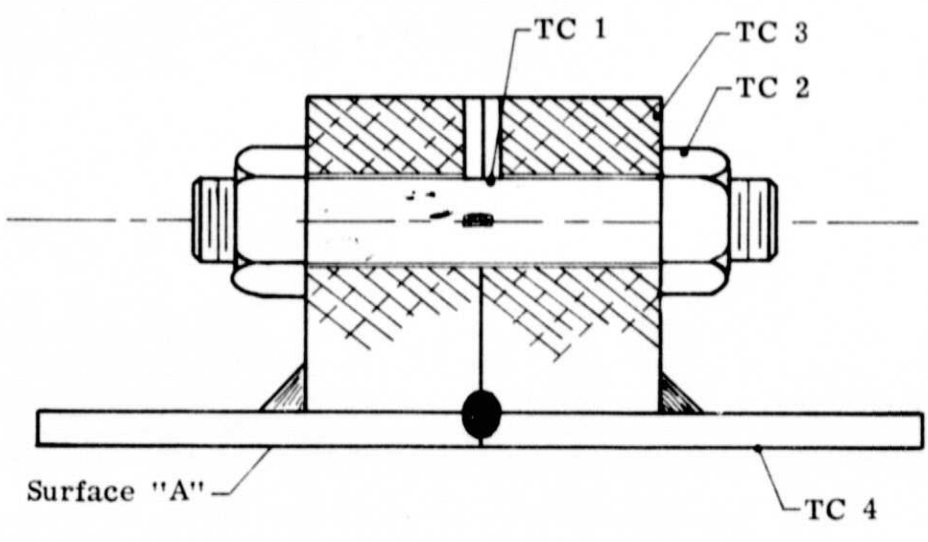

Figure 6. Pilot Cryo Tunnel bolt #2 calibration instrumentation.

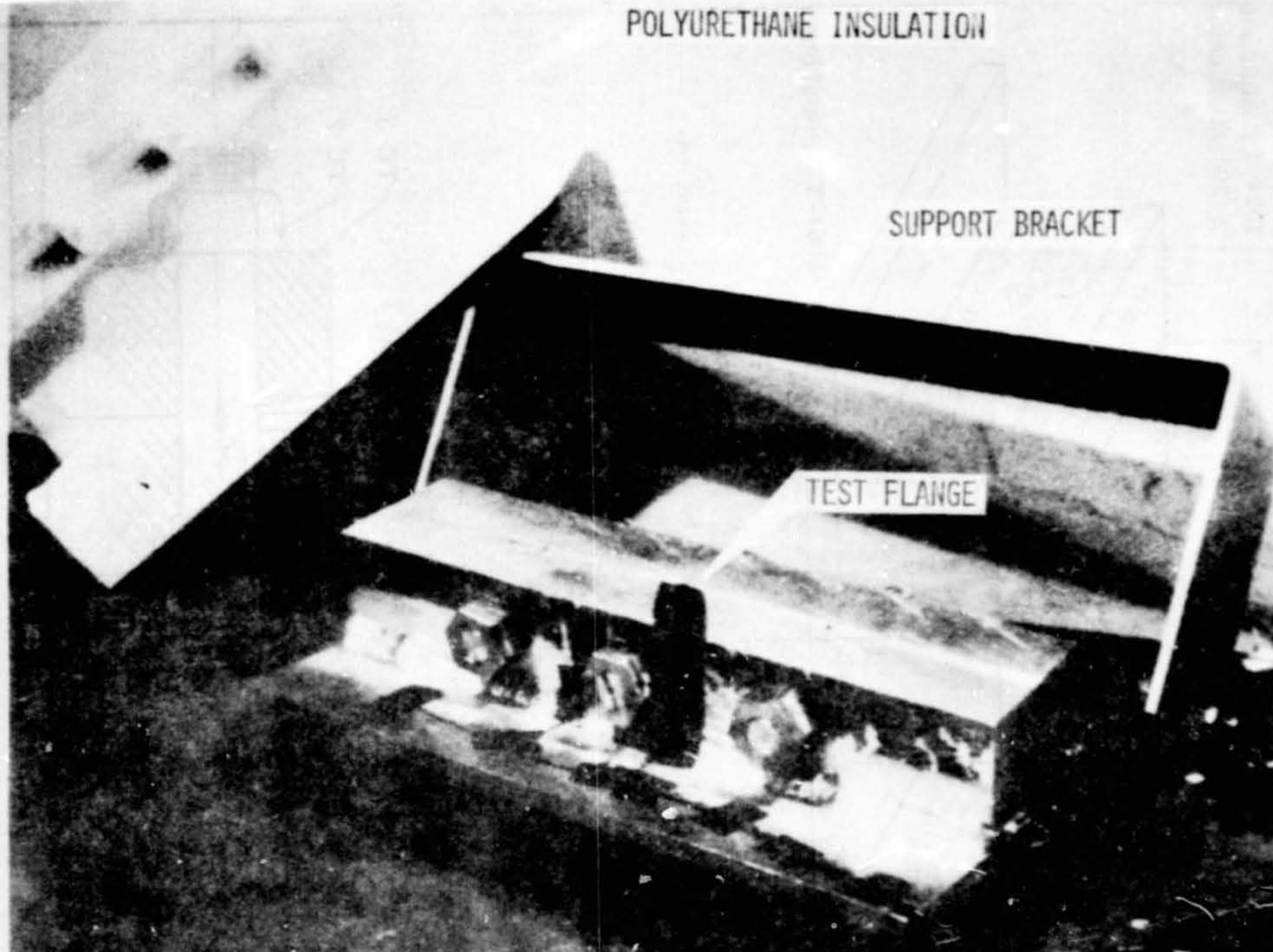

Figure 7. Pilot Cryo Tunnel bolt calibration configuration and insulation.

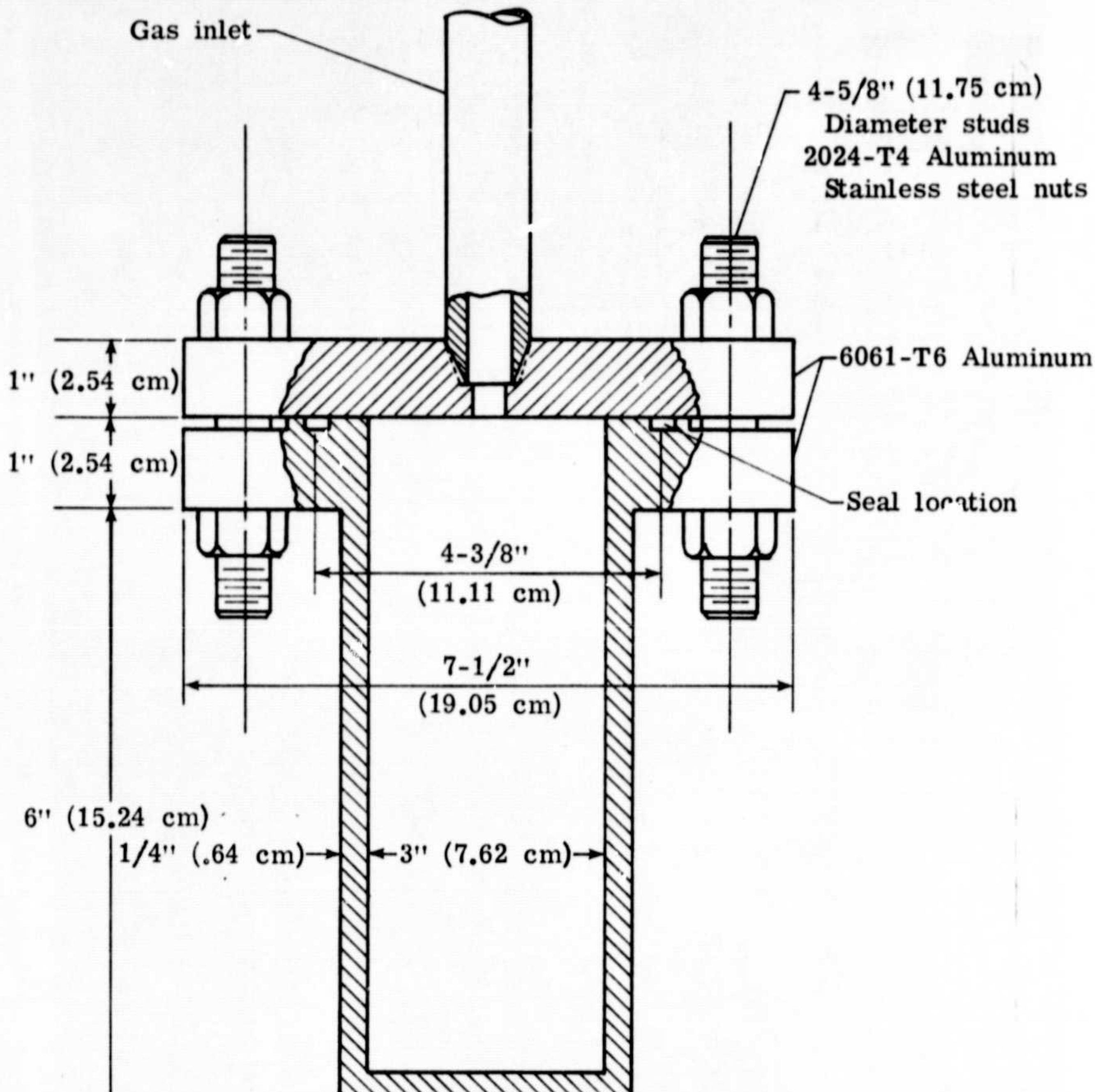

Figure 8. Pilot Cryo Tunnel seal test unit.

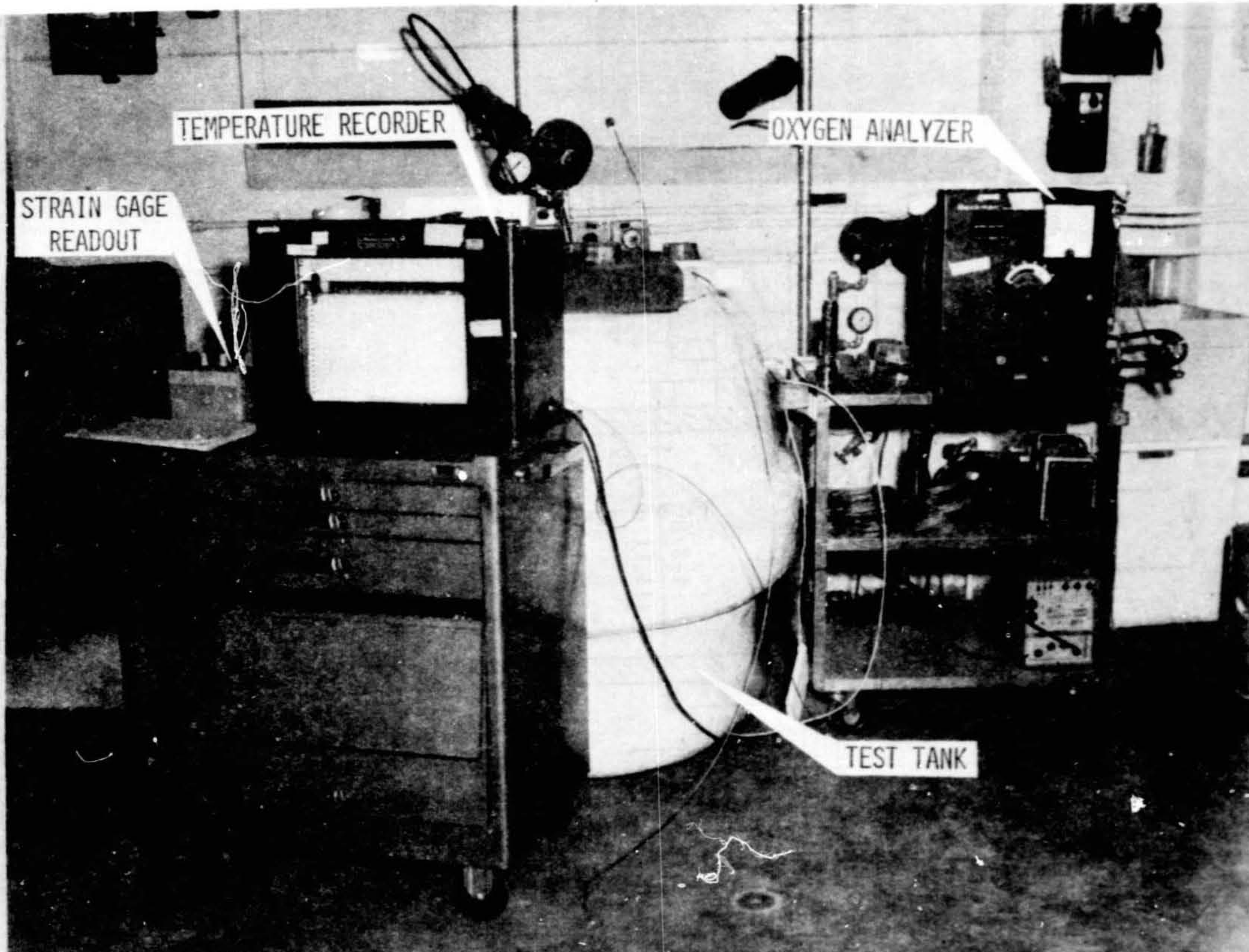

Figure 9. Pilot Cryo Tunnel test tank and equipment.

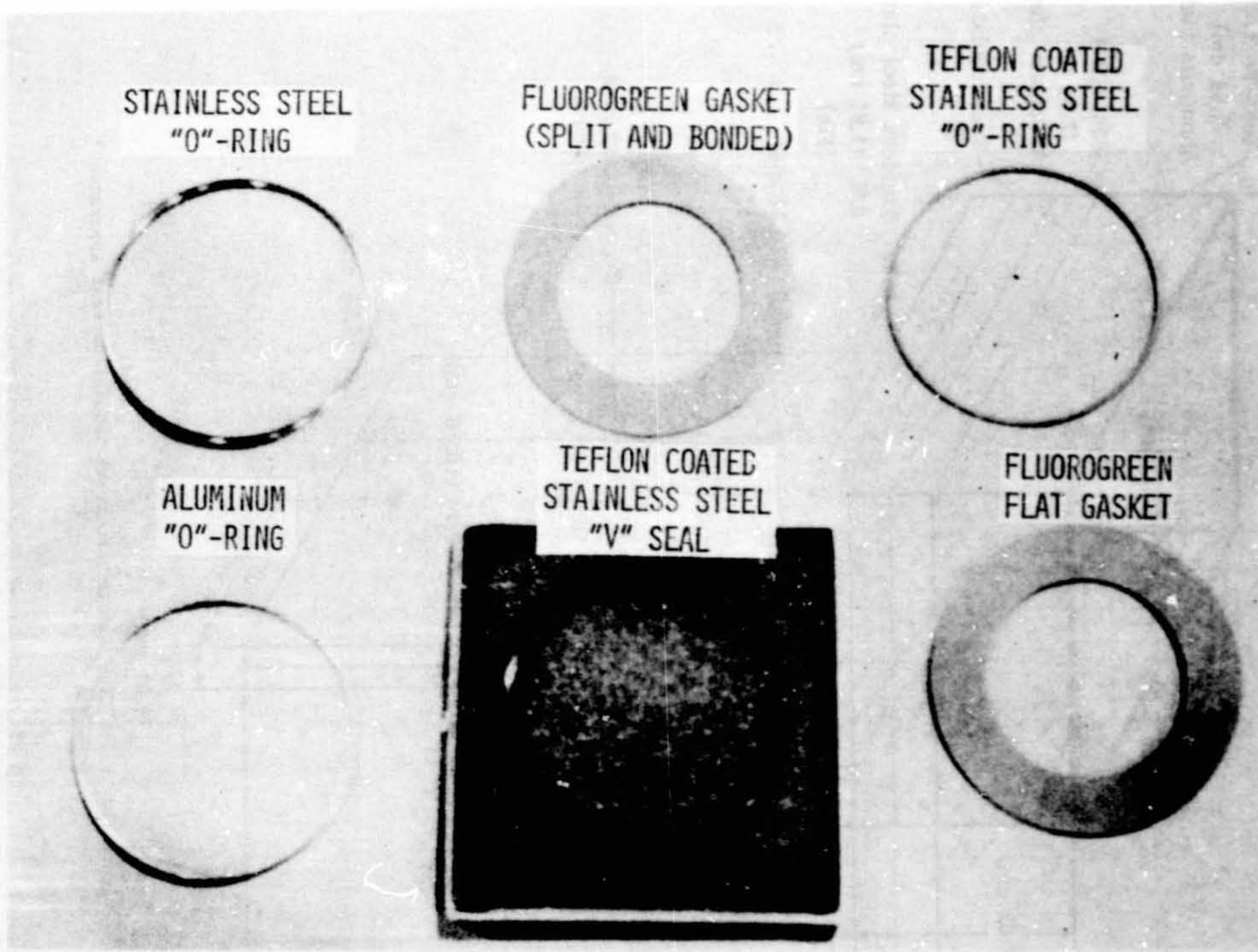

Figure 10. Pilot Cryo Tunnel seal configurations.

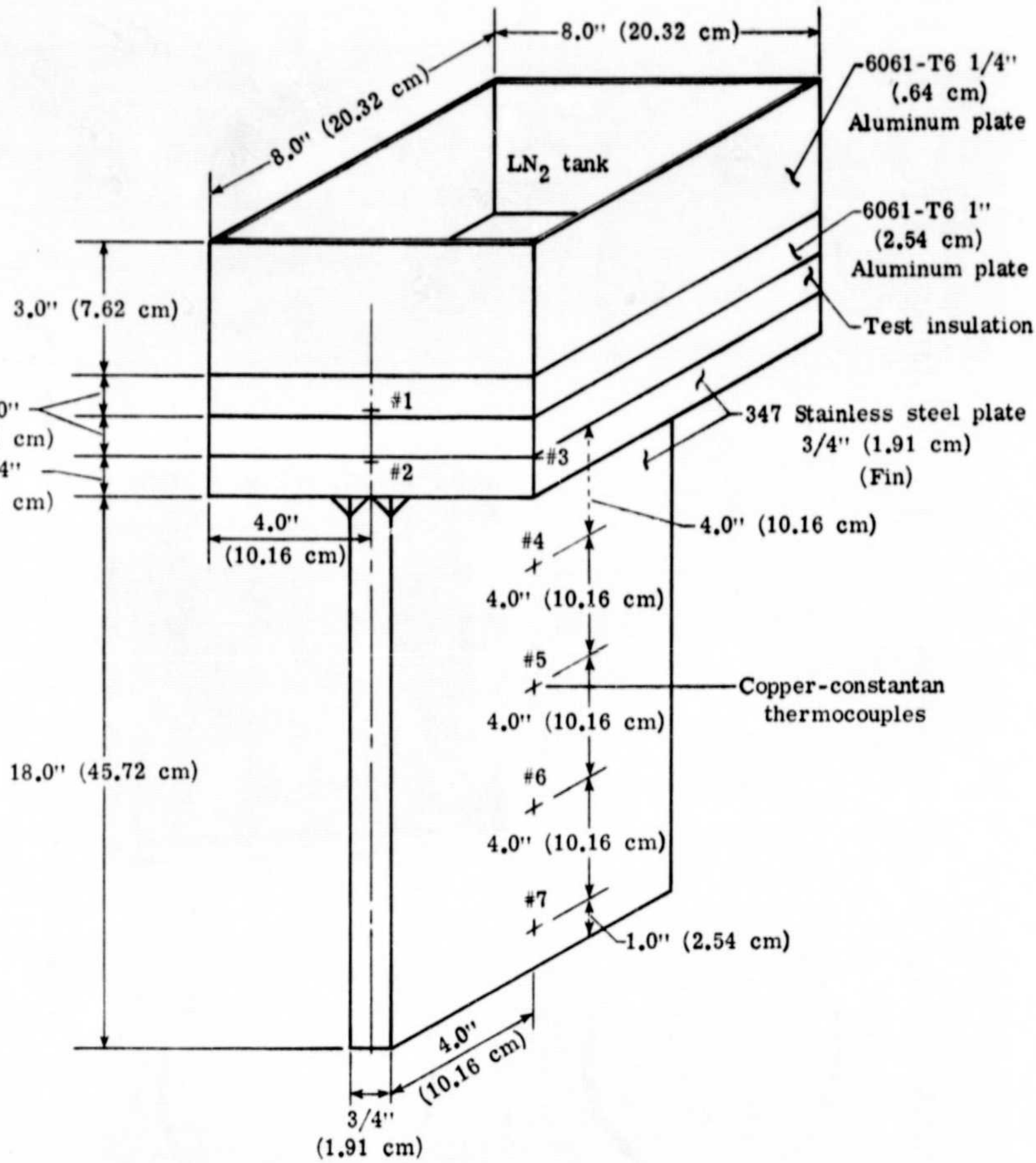

Figure 11. Pilot Cryo Tunnel structural insulation test apparatus.

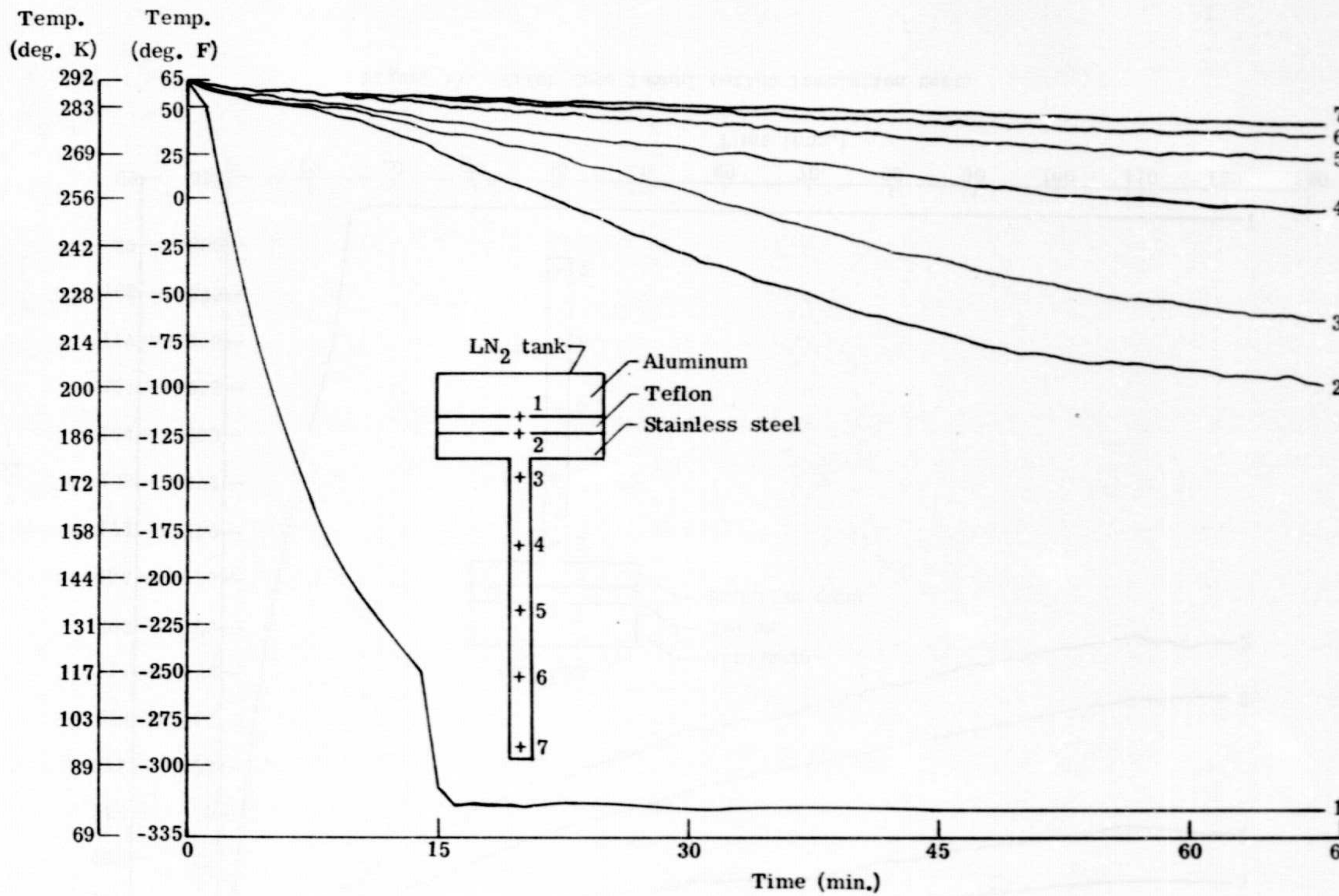

Figure 12. Pilot Cryo Tunnel teflon insulation test.

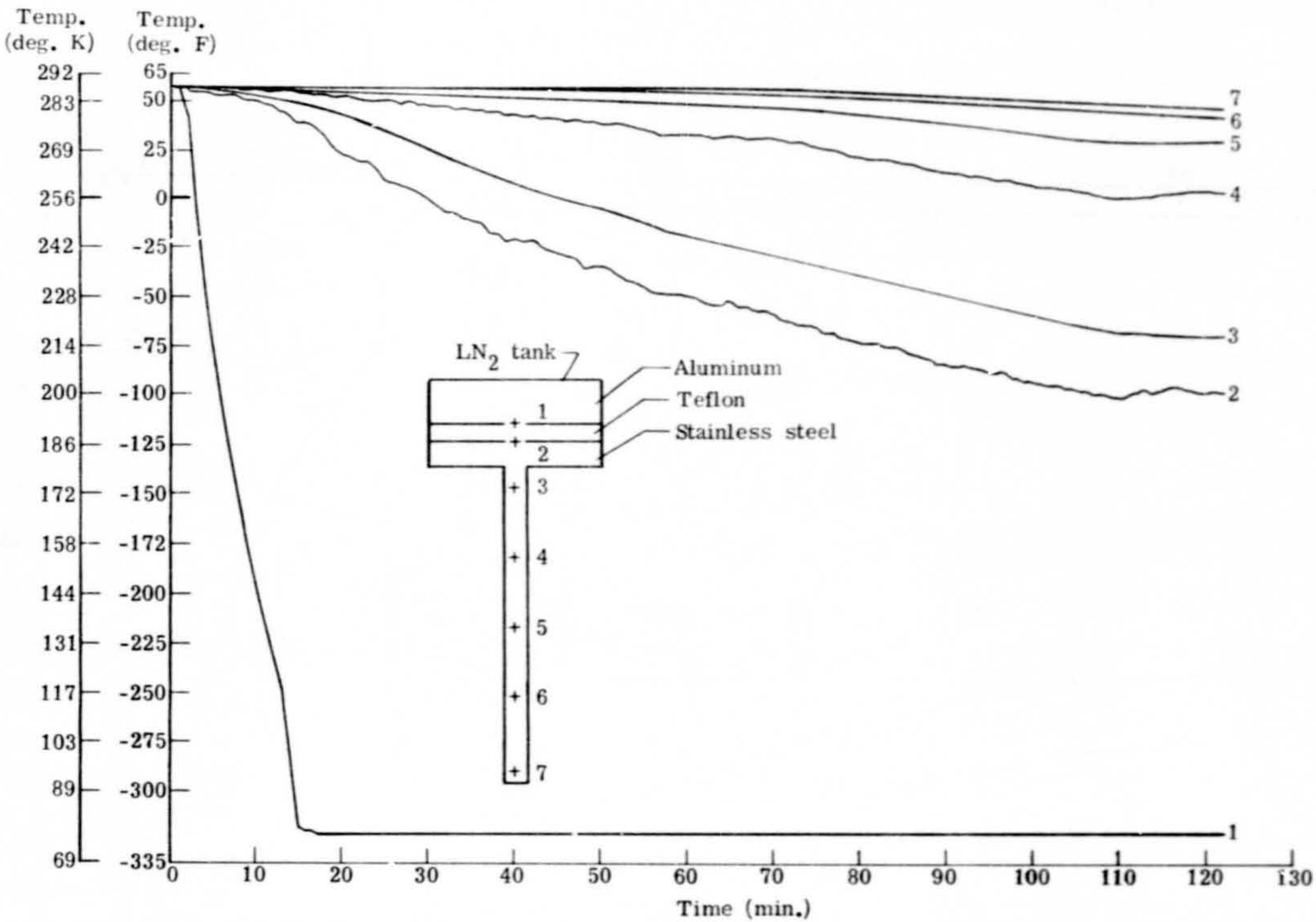

Figure 13. Pil-- Cryo Tunnel teflon insulation test.

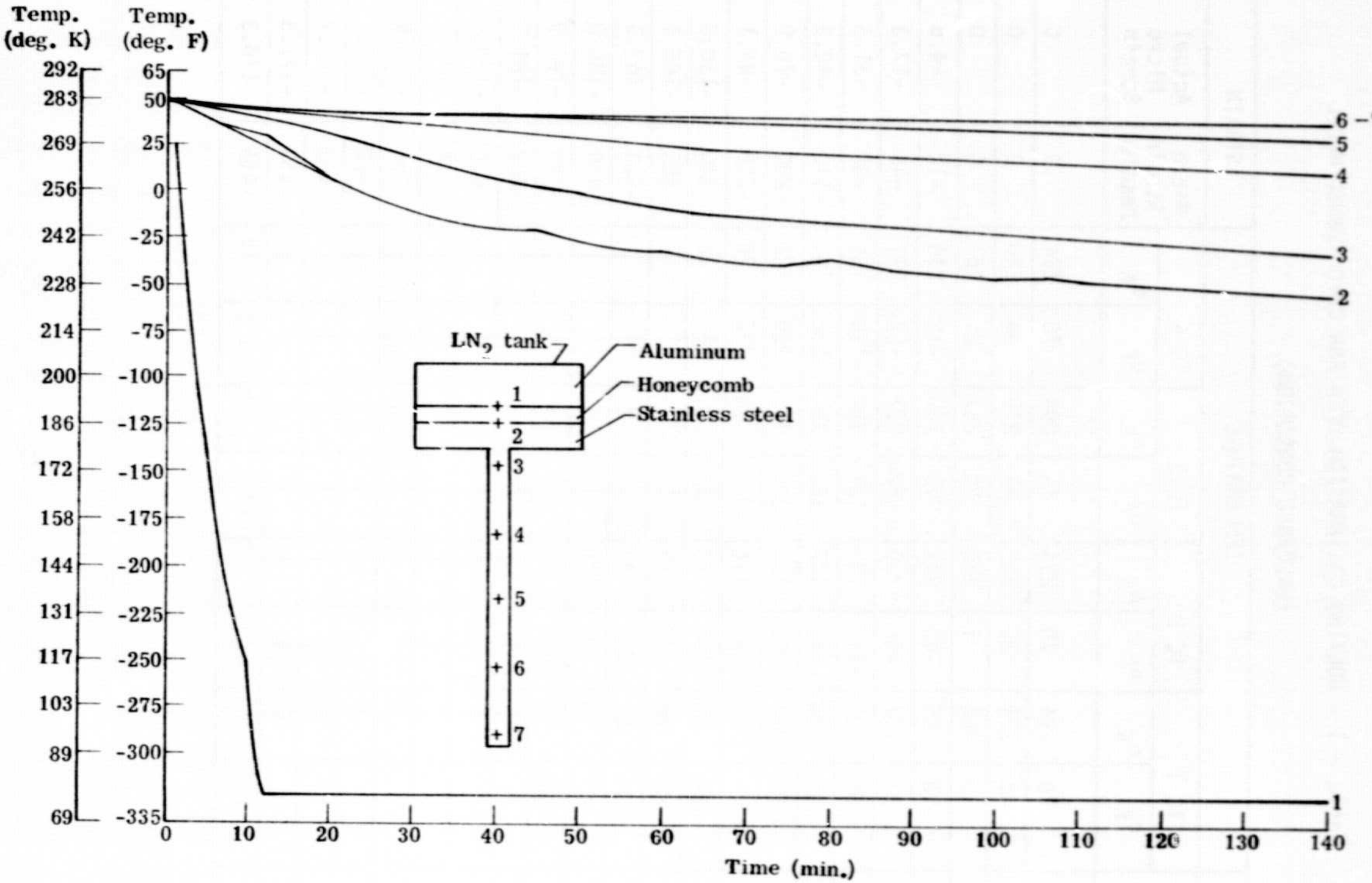

Figure 14. Pilot Cryo Tunnel honeycomb insulation test

Table - 1 - BOLTING CALIBRATION DATA FOR CRYO TUNNEL MODEL

(UNLOADED CONDITION)

	TEMPERATURE								STRAIN	
Time (Min)	TC 1		TC 2		TC 3		TC 4		Micro Strain Reading	Actual Micro Strain
	°F	°K	°F	°K	°F	°K	°F	°K		
0	70	294	70	294	70	294	70	294	0	0
5	43	279	22	268	43	279	44	280	0	0
9	19	266	1	256	20	267	21	267	0	0
15	-19	245	-43	232	-19	245	-19	245	-12	-4.6
22	-51	227	-64	220	-52	227	-52	227	-45	-17.3
31	-95	203	-112	193	-128	184	-126	186	-82	-31.5
36	-125	186	-141	177	-182	154	-188	151	-110	-42.3
53	-207	141	-223	132	-238	123	-226	130	-200	-76.9
59	-241	122	-252	116	-322	78	-322	78	-250	-96.1
70	-288	96	-292	93					-340	-130.8
82	-308	84	-310	83					-385	-148.1
89	-312	82	-314	81					-423	-162.7
103	-318	79	-320	78					-468	-180.0
118	-322	78	-322	78					-499	-191.9
132									-472	-181.5
148									-470	-180.8
163									-466	-179.2
178									-465	-178.8
192									-462	-177.7
208									-462	-177.7
223									-461	-177.3
238	-322	78	-322	78	-322	78	-322	78	-459	-176.3

Table - 2 - BOLTING CALIBRATION DATA FOR CRYO TUNNEL MODEL

(LOADED CONDITION)

	TEMPERATURE								STRAIN	
Time (Min)	TC 1		TC 2		TC 3		TC 4		Micro Strain Reading	Actual Micro Strain
	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK		
0	71	295	71	295	71	295	72	296	8270	3180
15	-119	189	-122	188	-151	172	-150	172	8094	3113
30	-322	78	-322	78	-322	78	-322	78	8090	3111
45									8086	3110
75									8092	3112
105									8087	3110
135									8092	3112
165									8098	3115
195									8097	3114
225	-322	78	-322	78	-322	78	-322	78	8099	3115

Table 3 - SEAL TEST DATA FOR CRYO TUNNEL MODEL

RUN NUMBER	SEAL		TOTAL BOLT ELONGATION		TEST GAGE PRESSURE (HELIUM		LEAK RATE @			COMMENTS
	MATERIAL	TYPE	(IN)	(mm)	(PSI)	(kPa)	$70^{0}F$ $(294^{0}K)$	$-320^{0}F$ $(78^{0}K)$	AFTER ONE TEMP CYCLE	
1	Fluorogreen E-609	Gasket (Flat)	.002	.051	60	413.7	None	None	None	Satisfactory
2	"	"	.005	.127	60	413.7	None	None	None	Reusable
3	"	"	.003	.076	58	399.9	None	None	None	Reusable
4	"	"	.005	.127	58	399.9	None	None	None	Reusable
5	"	"	.006	.152	58	399.9	Slight	None	None	Reusable with added bolt load
6	"	"	.006	.152	56	386.1	None	None	None	Reusable
7	"	"	.006	.152	56	386.1	None	None	None	Reusable
8	Viton-A	O-Ring (Rubber)	Metal to Metal	Metal to Metal	59	406.8	None	None	None	Satisfactory
9	"	"	"	"	59	406.8	None	None	None	Reusable
10	Aluminum 1100	O-Ring (Solid)	"	"	60	413.7	Slight	No Test	No Test	Unsatisfactory
11	Stainless 17-7	"V" Teflon Coated	"	"	59	406.8	None	None	None	Satisfactory
12	"	"	"	"	59	406.8	None	None	None	Reusable

Table 3 (Continued) - SEAL TEST DATA FOR CRYO TUNNEL MODEL

RUN NUMBER	SEAL		TOTAL BOLT ELONGATION		TEST GAGE PRESSURE (HELIUM)		LEAK RATE @			COMMENTS
	MATERIAL	TYPE	(IN)	(mm)	(PSI)	(kPa)	$70^{O}F$ ($294^{O}K$)	$-320^{O}F$ ($78^{O}K$)	AFTER ONE TEMP CYCLE	
13	Stainless 304	O-Ring (Hollow)	Metal to Metal	Metal to Metal	60	413.7	Fast	No Test	No Test	Unsatisfactory
14	Stainless 321	O-Ring Teflon Vented	"	"	57	393.0	None	None	None	Satisfactory
15	"	"	"	"	57	393.0	None	None	None	Reusable
16	Fluorogreen E-609 split & bonded	Gasket (Flat)	.003	.076	59	406.8	Fast	No Test	No Test	Unsatisfactory
17	"	"	.005	.127	58	399.9	Slight	No Test	No Test	Unsatisfactory
18	"	"	.005	.127	58	399.9	None	Slight	None	*Bad Joint
										*Bad Bond on Fluorogreen Gasket